What is the Effect of Climate Warming on Streamflow in Snow-Dominated Catchments?

- Naomi Tague
  - Warming can in some cases lead to significant declines in forest water use,
    so streamflow would increase

- Ross Woods
  - With warming, the proportion of precipitation falling as snow would decrease,
    so streamflow would decrease

A Warming Climate Will Significantly Reduce Streamflow from Snow-Dominated Catchments

Ross Woods & Wouter Berghuijs

Department of Civil Engineering, University of Bristol, United Kingdom

University of BRISTOL

Impacts of Warming Climate on Streamflow in Snow-Dominated Catchments

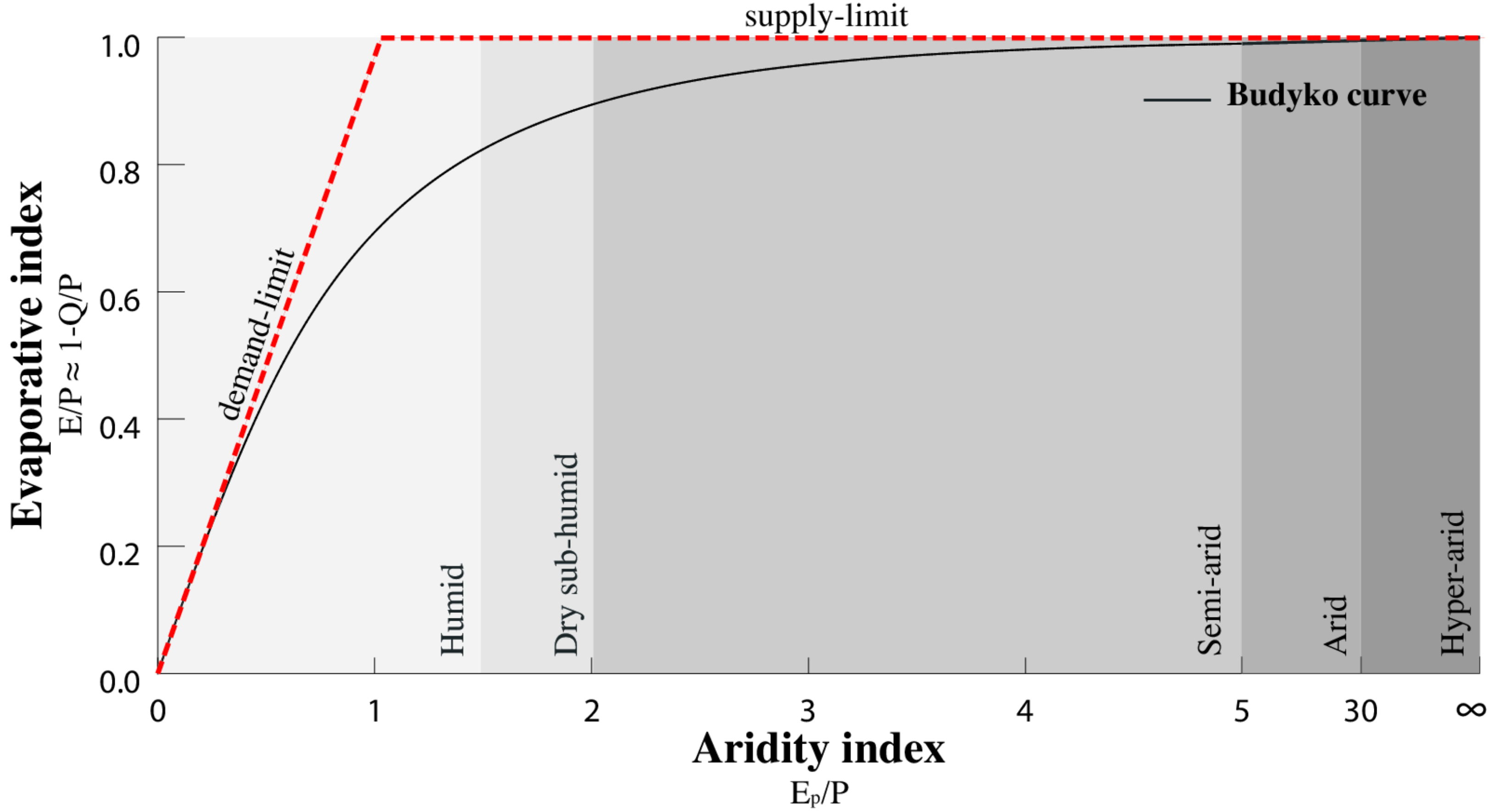
- We already know about impacts on seasonal flow
  - Warmer climate will produce rain instead of snow
  - Snowpacks will be smaller, snowmelt peak earlier
  - This effect has already been observed in western USA (e.g. Stewart et al 2005 J.Clim), though with questions …
    - attribution: is ΔT really the cause? (Luce et al, 2013, Science)
    - the centre-of-volume metric (Whitfield, 2013, Hydrol. Proc.)
- Will the mean flow change in snowy catchments?
  - Until the start of 2014, most studies of warming for snowy catchments suggested changes in the mean flow could be neglected, because
    - No obvious mechanism, and no convincing data

Budyko Hypothesis for Water Balance

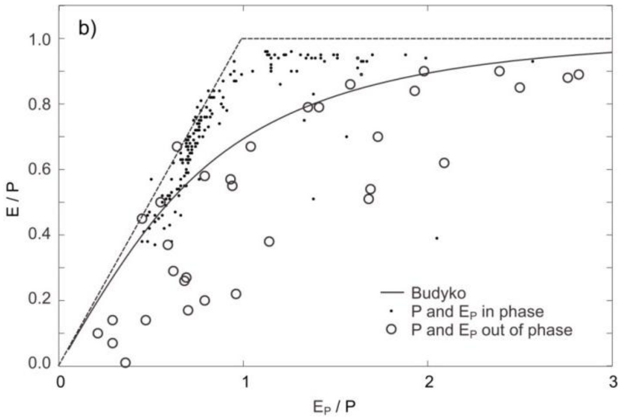
- Hypothesis: The evaporative fraction (ε=E/P) is mainly a function of the aridity or dryness index (Φ=Ep/P),
  i.e. E/P ≈ F(Ep/P)
  - E = actual evaporation
  - P = precipitation
  - Ep = potential evaporation
- Limited to
  - sufficiently long timescales (so that change in catchment storage is small), e.g. 5-50 years
  - sufficiently large space scales (to limit the variation due to the influence of local conditions of a non-climatic character),
    e.g. > 1000 km^2
- A structured framework to control for the effect of climate

e.g. Budyko 1974, Donohue et al, HESS 2007

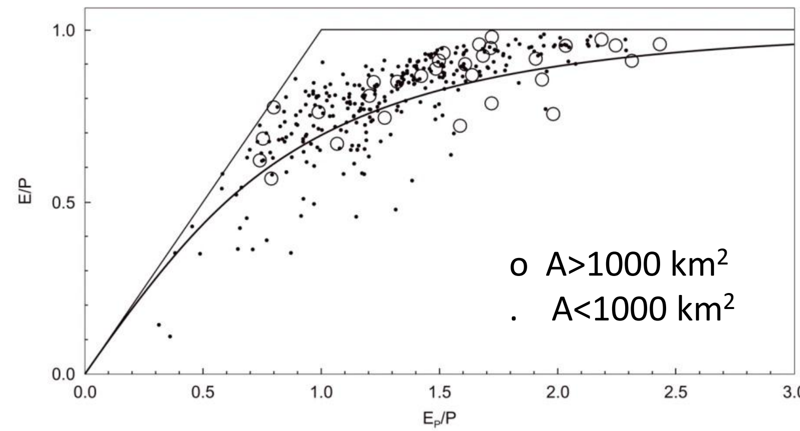
Budyko Curve



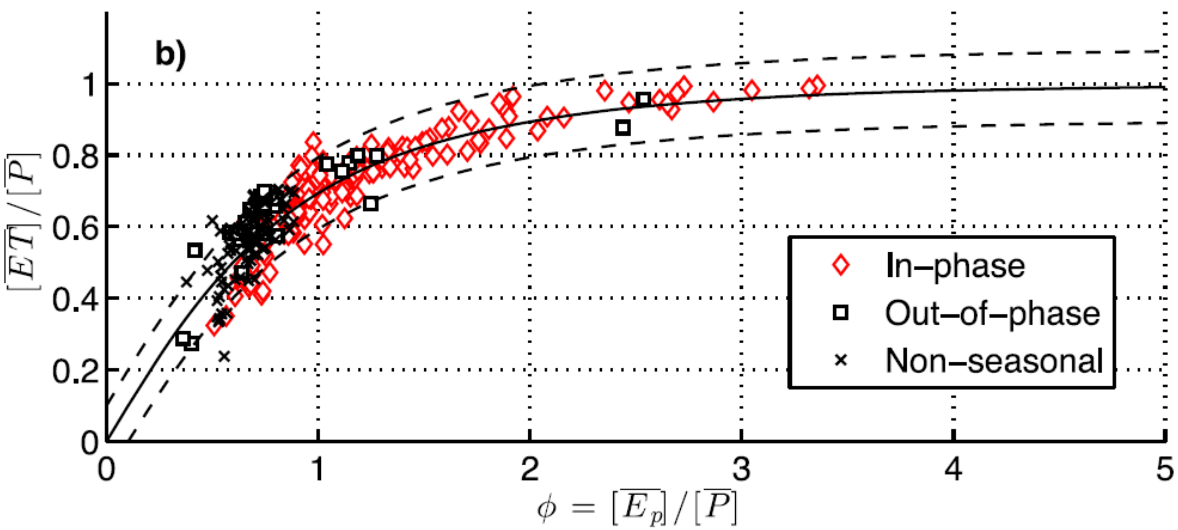
Example Studies



344 USA climate divisions
Wolock and McCabe (1999)



331 Australian catchments
Donohue et al (2007)



(431-77) USA catchments
Gentine et al (2012)

Data cluster about the Budyko curve, but …
Tightness of clustering varies!
Some patterns in scatter …
Is this a success?

Snowiness Explains (some) Scatter!

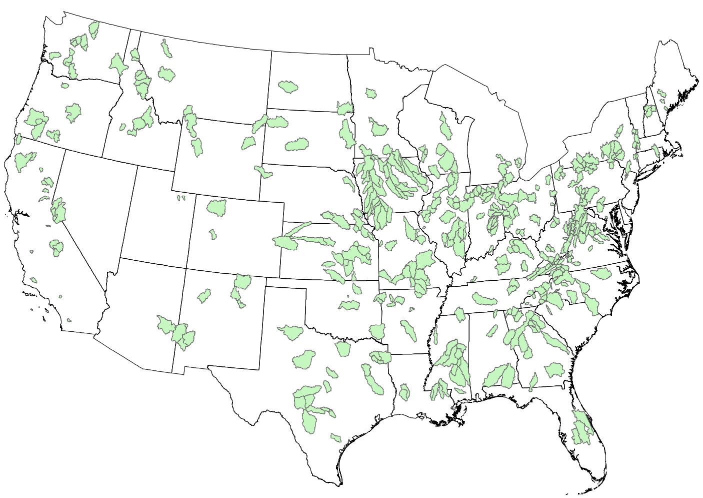
The Findings

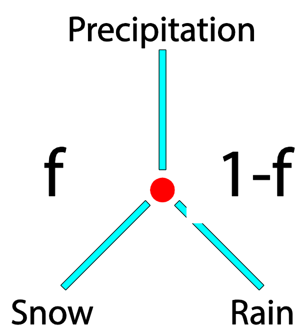
- For catchments in the US MOPEX set
  - Catchments with more snowfall (as a fraction of total precipitation) produce more streamflow, other things being equal
  - For any particular catchment, periods with more snowfall (as a fraction of total precipitation) also have more streamflow, other things being equal
- This seems to be a new finding: no prior demonstration that snowiness (snowfall/precipitation) affects mean flow
- This effect is quite important and relevant
  (I'm not going to give the whole story away yet!)

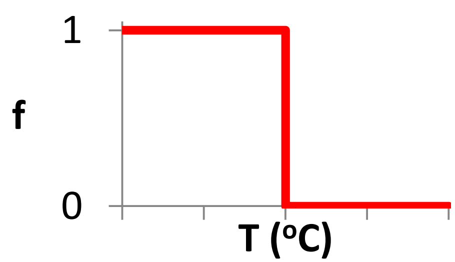
Berghuijs, Woods and Hrachowitz (Nature Climate Change, 2014)

Data

- From the US MOPEX dataset which consists of 420 catchments located across the contiguous USA
- P, Ep, Tair, Q daily catchment series
- Snowfall is calculated from P and Tair on a daily basis and aggregated over time

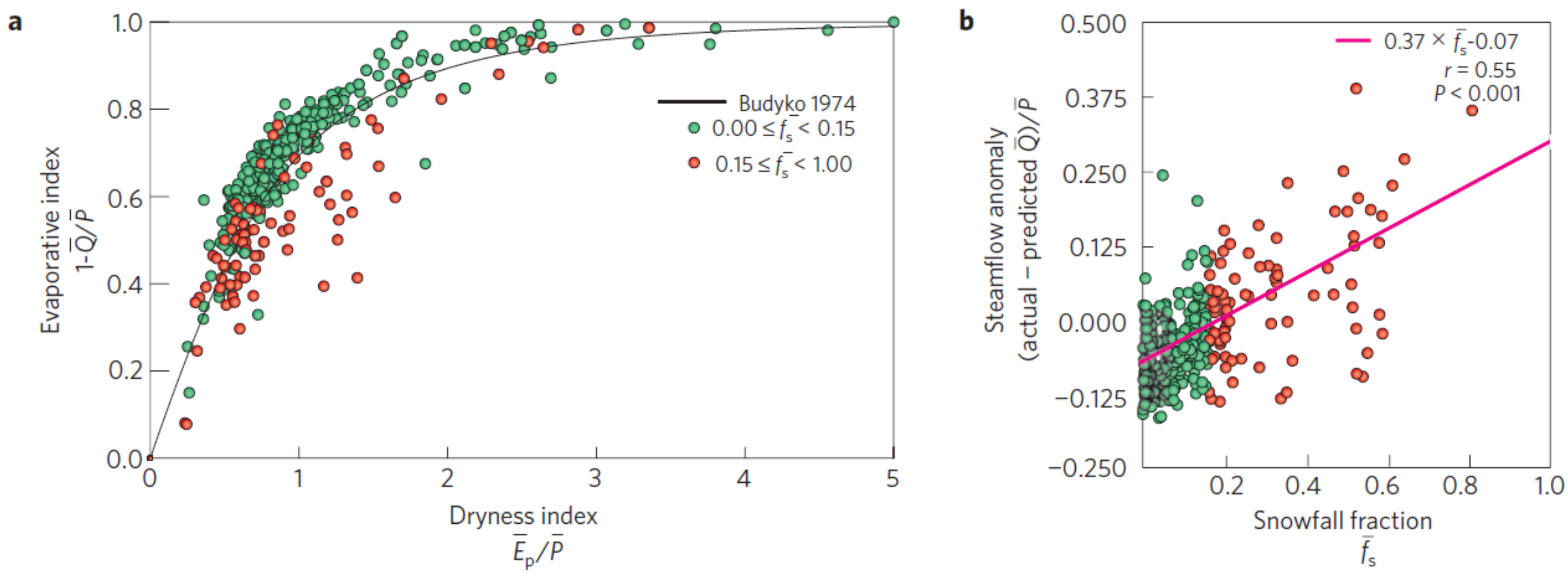






Schaake, J., Cong, S., & Duan, Q. (2006). The US MOPEX data set. IAHS Publication 307, 9-28.

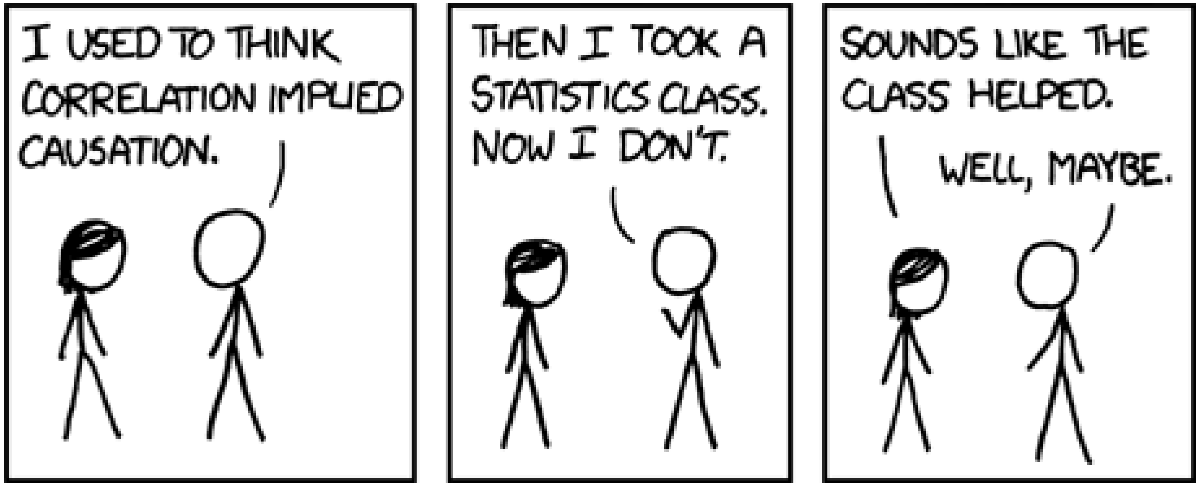
Average annual data on a Budyko plot



- Departures below the Budyko curve are larger for snowier catchments, so catchments in the USA with more snow tend to have higher mean streamflow, for a given climate
- This signal is, by definition, from data points that don't "fit"
- This is an interesting correlation, but is there more to it?

Just a correlation?

- We found that more snow is associated with more streamflow
- Is snow the cause of this?
- It might be that snow is correlated with some other factor (e.g. elevation, slope, temperature) which is the ‘real’ cause

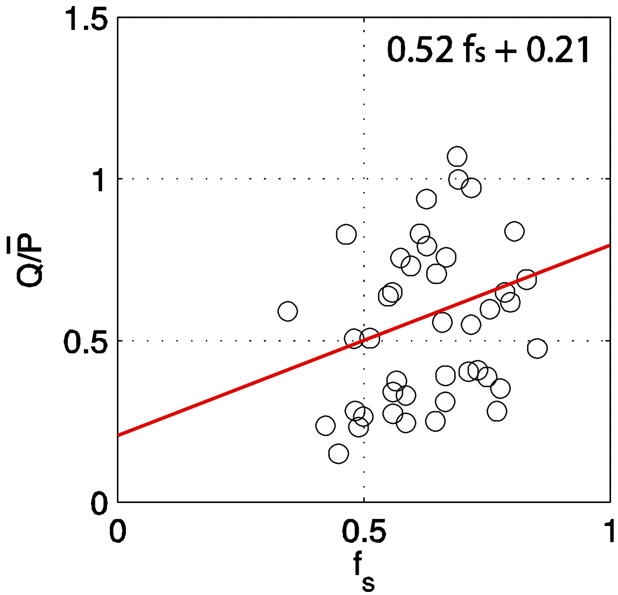


xkcd.com/552/

- So now let’s look at interannual variability. For each catchment, do snowier periods produce more streamflow?
- If we find an effect, then we have eliminated all “static” causal factors (elevation, slope) as possible explanations

Interannual Variation

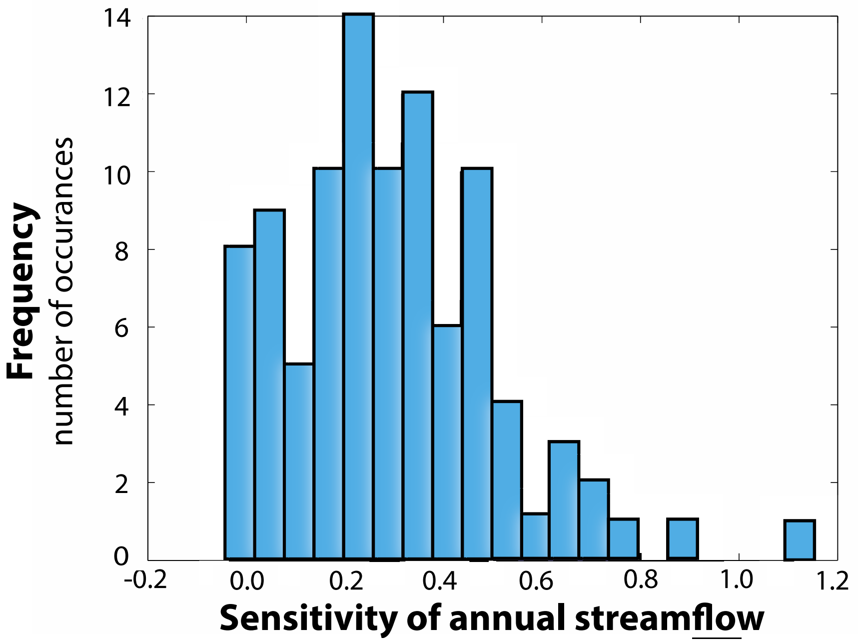
- We use linear regression to estimate the annual streamflow variation due to variations in the snow fraction.
- We take annual values of Q (normalised by the mean annual P), and plot them against fs, for each catchment
- Since annual P is a primary control on annual Q, we removed the effect of any correlation between annual P and annual fs
- The result is a measure of sensitivity of annual streamflow to annual fs for each catchment
- Analysis on 97 catchments with fs>0.15



$$\frac{\Delta(Q/\overline{P})}{\Delta f_s}$$

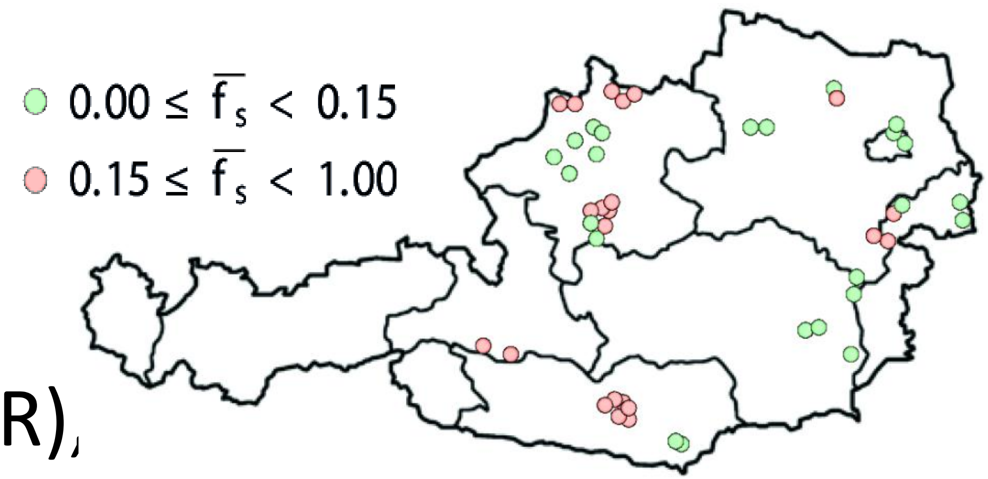
Interannual Results (USA)

- Sensitivity of normalised annual streamflow to annual fs is positive for 94 out of 97 catchments
- Years with higher snow fraction, fs, tend to have higher values of annual streamflow.
- Does carryover storage between years matter? No. If we use 5-year averages, we reach the same conclusion



$$\text{Sensitivity} = \frac{\Delta(Q/\overline{P})}{\Delta f_s}$$

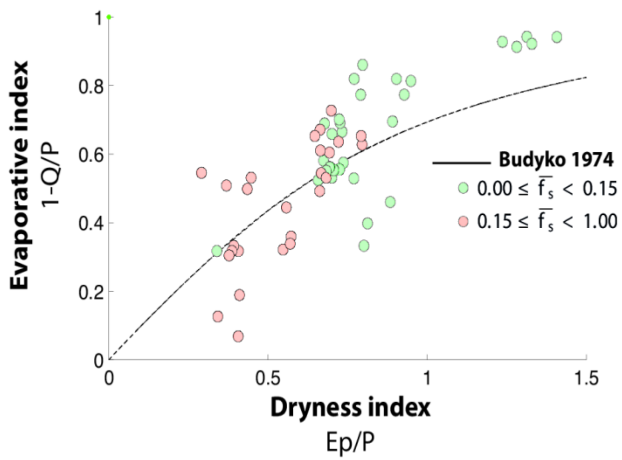
New Preliminary Results - AUSTRIA



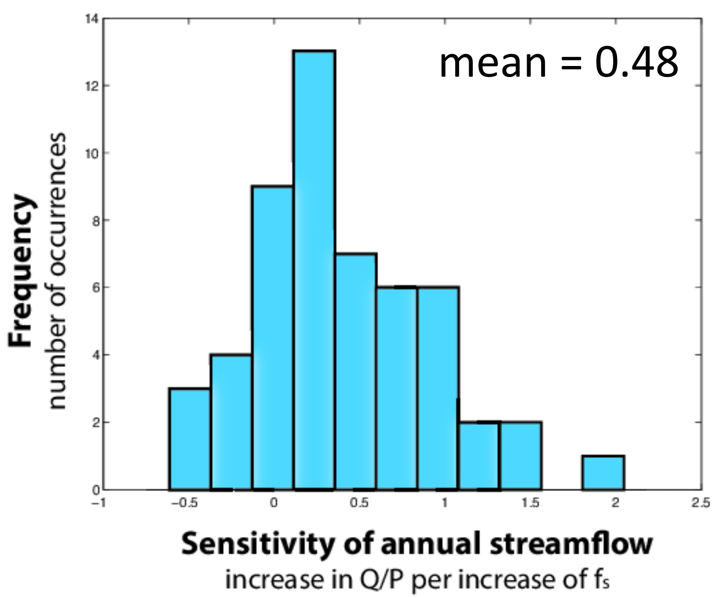
- 60 catchments from Gaal et al (2012, WRR), via Juraj Parajka, TU Vienna
- 22-33 years data (mean 31 years)
- Mean fs ranges from 10% to 55%
- We repeated the MOPEX-USA analyses to test the generality of our findings

Effect of Snow on Water Balance

Austria

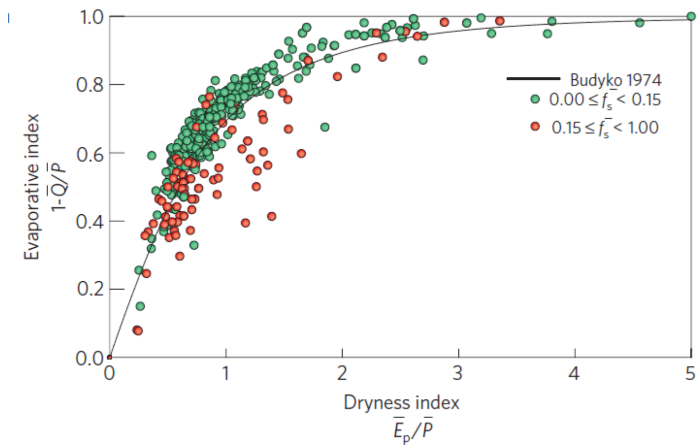


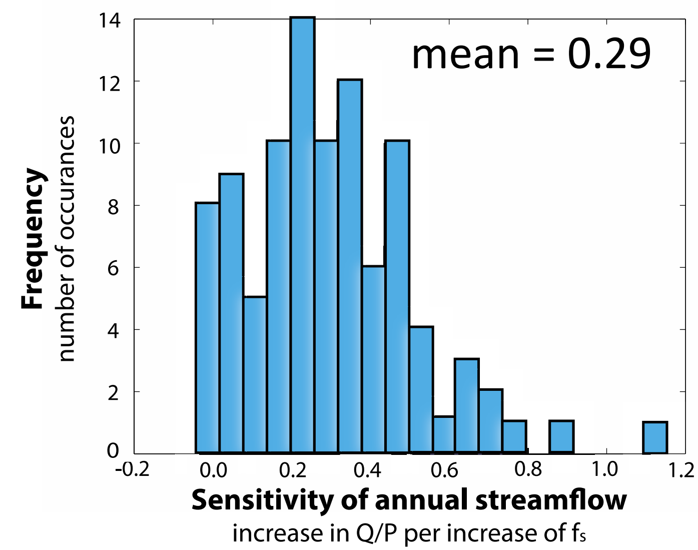
These snowy Austrian catchments don't deviate from the Budyko curve



Snowy Austrian catchments do usually produce more runoff in years with more snow

MOPEX (USA)





To Summarise so Far

- Catchments with more snow tend to have higher mean streamflow (USA)
  - Snow is not a surrogate for any static factor, because we also found that …
- Periods with higher snow fraction, fs, tend to have higher values of annual streamflow (USA & Austria)
  - We also found that this isn't purely an effect of low temperature, because the sensitivity is not consistently positive for summer temperatures, nor for catchments with fs<0.15 [not shown]

What is the Mechanism?

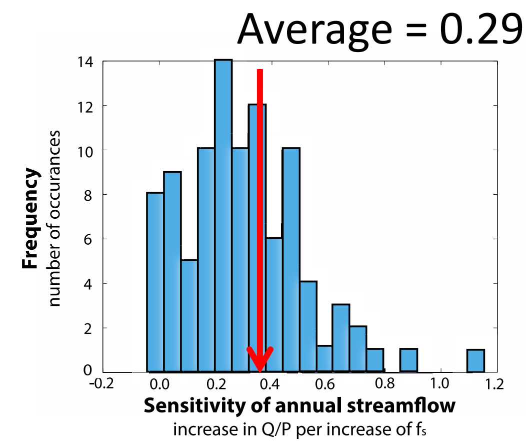
- We don’t know (yet)
- There is unlikely to be a single cause
- Potential explanations for how snowiness affects mean streamflow include effects via changes in
  - infiltration capacity of (frozen) soils,
  - duration/timing of infiltration (winter rain vs melt pulse)
  - evaporation from snow-covered vs snow-free soils
  - growing season length
  - soil moisture regime
- More work is needed on this

Who Cares?

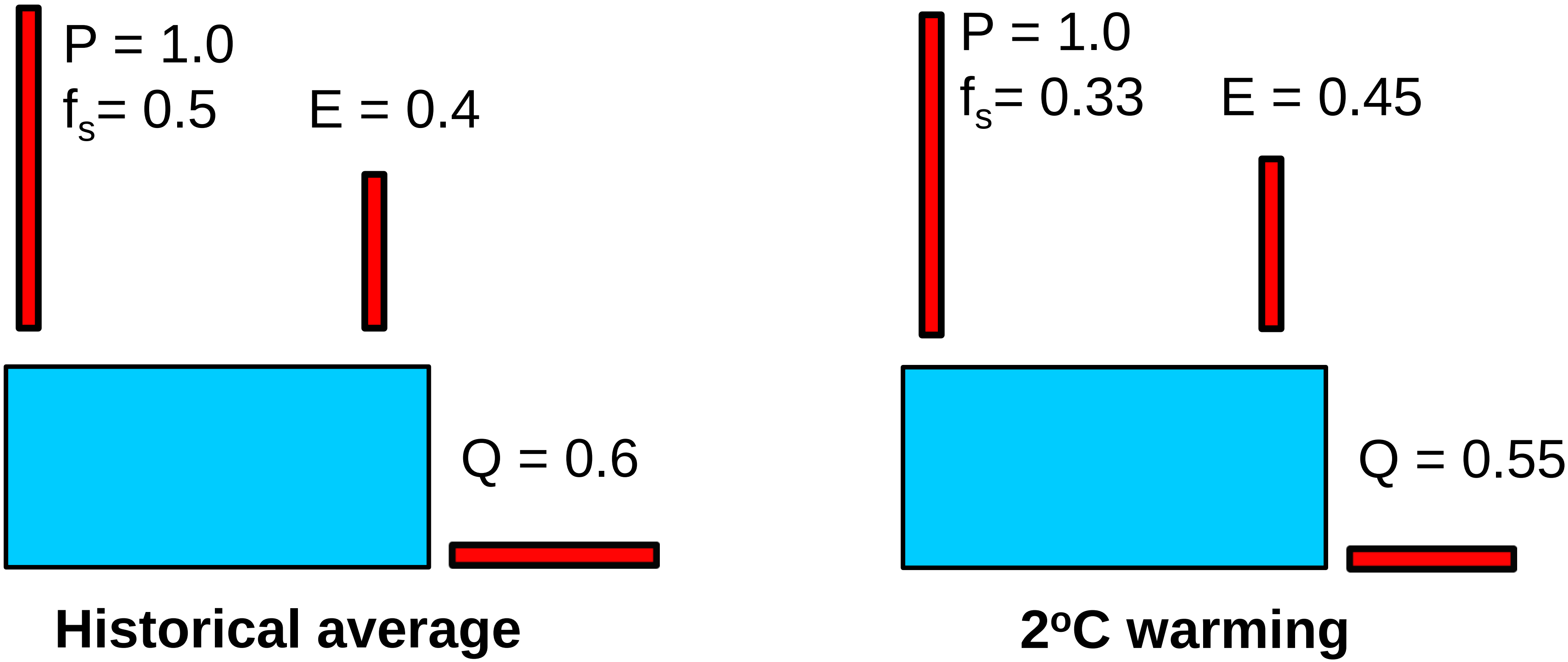
- Turn it around:
  - If more snow implies more streamflow, then
  - Less snow implies less streamflow
- In a warming climate, we expect less of the precipitation to fall as snow
- So, other things being equal, in a warmer climate, we expect mean streamflow to be lower than it would have been if climate had not warmed
- This is entirely separate from the impacts of warming on the seasonality of streamflow in snow-dominated catchments

How Much Lower?

- It varies between (and within) catchments
- Take a 2°C temperature rise, for example
- For the U.S. MOPEX data, a 2°C temperature rise leads to 35% decrease in fs, on average.
- Average sensitivity = 0.29 Q/P per unit fs
- This would imply that a 2°C temperature rise leads to decreases in normalized streamflow (Q/P) of the order of 0.10 [=0.35*0.29] times the historical fs (assuming no confounding effects).
- Remember these are only averages. The actual effect in any specific location could be quite different



For Example



- 2°C warmer in an average US MOPEX catchment with fs=0.5 leads to reduction in Q/P of 0.05
- Since current Q/P=0.6, then this is an 8% reduction in flow
- Greatest % reduction in flow is for large fs, small Q/P (snowy, arid)

Does Anyone Else Agree?

- Effect was hypothesised
  - Bosson et al (2012 JGR-Atmos) using modelling study (Sweden, 1 catchment)
- Also published in 2014
  - Reinfelds et al (2014, J.Hydrol): “Runoff coefficient sensitivity is driven by … the proportion of precipitation falling as snow vs. rain” (SE Australia, 95 catchments)
- … there are other reasons for flow decrease
  - Goulden and Balas (2014, PNAS): “Kings River flow is highly sensitive to vegetation expansion; <u>warming</u> … could increase ET … by 28% and <u>decrease riverflow</u> by 26%.” (CA, USA, 12 catchments)

What Next?

- Same study with other sets of data
  - The US catchments are quite diverse, so we would be quite surprised not to find the effect elsewhere
  - More studies would increase sample size
  - More detailed examination of Q reduction
- Studies of potential mechanisms
  - Can we eliminate some mechanisms?
  - Do existing multi-year field studies in particular places reveal mechanisms in action?

In Closing

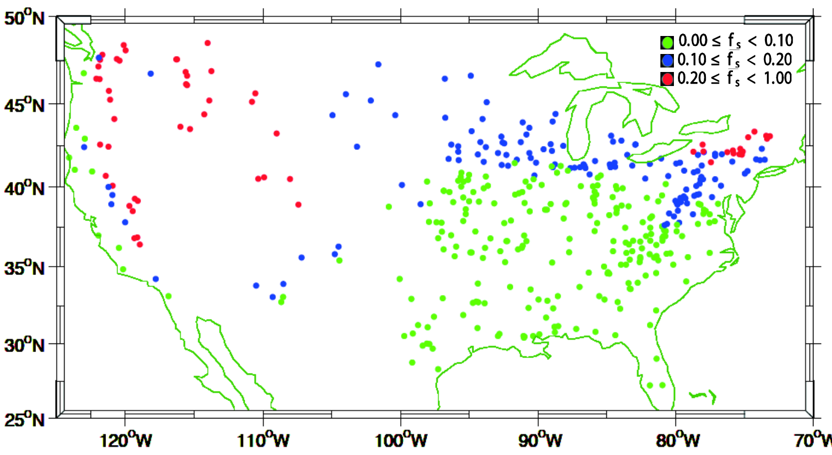
- The Budyko curve identifies the influence of mean climate, and provides a structured way to look at other drivers of streamflow. Budyko is helpful for the things it does not predict
- Catchments with less snow tend to have lower mean streamflow
- Periods with lower snow fraction, fs, strongly tend to have lower values of annual streamflow, for given precipitation
- A warming climate is expected to lead to a lower snow fraction, and, other things being equal, lower annual streamflow. Order of magnitude estimate: 5-10% reduction, but with significant variations around this
- Snow-fed catchments are frequently "water towers" for society, and so lower mean streamflows there would provide extra challenges for water management

Why Did No-one Notice Before?

- Total precipitation varies a lot in time and space, and it has dominant effect on mean streamflow
  - Any other effect on streamflow is 2nd-order, and not easily detected
  - There are multiple competing 2nd-order effects, and it is not easy to isolate one of them (in this case, snowfall)
- The snow-affected catchments were sometimes excluded from studies because
  - the results didn't fit the expected pattern(?)
  - the precipitation was thought unreliable (snow is hard to measure)
- There was (and still currently is) no obvious single mechanism, so there was no simple hypothesis to test

Data Details

- US MOPEX
  - c. 50 years of data
  - High raingauge density (Schaake formula)
  - Raingauges interpolated using PRISM
  - Wide variety of settings
  - Limited anthropogenic influence
  - No large glaciers



- We corrected raingauges for undercatch (Groisman and Legates 1994). Without correction, the snow effect is stronger
- Robust to changes in snowfall estimation
- Streamflow measurement errors and exchanges with aquifers can bias results of individual catchments, but are unlikely to be strongly correlated to the snow fraction.

One Curve to Rule Them All?

- One curve?
  - Naïve view: if the only control is mean climate, then we predict that there is no effect of other factors (seasonality, soils, veg, topography)
  - Sophisticated view: this does lead to interesting research questions, if you study systems that have been undisturbed (by humans <u>and</u> nature) for long enough that they have co-evolved to the curve
- Many curves?
  - There are many places where other factors have an influence
  - If there are multiple curves, then they should be linked to one another. Put another way, we need to explain patterns in the scatter

Comments regarding the original MOPEX study

- It's not just a 'timing of P' issue, because we can see similar results by looking at T

Cold season:
pronounced effect

Warm season:
no effect

Spring:
some effect